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WOOD AND OTHER RENEWABLE RESOURCES

Analysis of raw cork production in Portugal and Catalonia using life cycle assessment

Ana Cláudia Dias · Jesús Boschmonart-Rives · Sara González-García · Martha Demertzi · Xavier Gabarrell · Luis Arroja

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Abstract
Purpose This study aims to (1) evaluate the environmental impacts associated with the three types of raw cork produced in Portuguese cork oak woodlands (in Alentejo region) considering two alternative practices for stand establishment (plantation and natural regeneration), (2) compare the environmental impacts of raw cork production in Portuguese cork oak woodlands and in Catalonian cork oak forests, and (3) assess the influence of different allocation criteria for partitioning the environmental impacts between the different types of raw cork produced.

Methods A cradle-to-gate approach was adopted starting with stand establishment up to cork storage in a field yard. The system boundaries include all management operations undertaken during the following stages: stand establishment, stand tending, cork stripping, and field recovery. The allocation of the environmental impacts to reproduction, second, and virgin cork was based on mass and market price criteria. An alternative allocation approach was simulated by allocating environmental impacts also to the wood produced in the cork oak stands. The impact assessment was performed using the characterization factors recommended by the International Reference Life Cycle Data System (ILCD).

Results and discussion In Portugal, cork produced from naturally regenerated stands has a better environmental performance than cork produced from planted stands, but the differences are smaller than 10 %. Different management models of cork oak stands in Portugal and Catalonia (agro-silvopastoral system and forest system, respectively) originate different impact levels, which tend to be significantly lower in Catalonia. The environmental hot spots in the two regions are also distinct. In Catalonia, they are associated with cleaning, road maintenance, and worker and cork transport. In Portugal, they are fertilization, pruning, and cleaning. The two allocation criteria affect significantly the results obtained for virgin cork in Portugal and for virgin and second cork in Catalonia. Besides, when impacts are also allocated to wood, mass allocation should be avoided as it would not create incentives for a sustainable management of cork oak stands.

Conclusions The environmental impact from Catalonian cork may be reduced by decreasing mechanized shrub cleaning and road maintenance operations through the introduction of livestock in cork oak forests, and also by a better planning of management operations. For the Portuguese cork, improvements may be achieved by optimizing fertilizer dosage, planting nitrogen-fixing crops and pastures that improve soil

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A. C. Dias (✉) · S. González-García · M. Demertzi · L. Arroja
Centre for Environmental and Marine Studies (CESAM),
University of Aveiro, 3810-193 Aveiro, Portugal
e-mail: acdias@ua.pt

J. Boschmonart-Rives
Inèdit Innovació SL, Carretera de Cabrils, km 2 (IRTA),
08348 Cabrils, Spain

J. Boschmonart-Rives · X. Gabarrell
Sostenipra (ICTA-IRTA-Inèdit), Institute of Environmental Science and Technology (ICTA), Universitat Autònoma de Barcelona (UAB), Bellaterra (Cerdanyola del Vallès), 08193 Barcelona, Spain

S. González-García
Department of Chemical Engineering, Institute of Technology, University of Santiago de Compostela, 15782 Santiago de Compostela, Spain

A. C. Dias · S. González-García · M. Demertzi · L. Arroja
Department of Environment and Planning, University of Aveiro, 3810-193 Aveiro, Portugal

X. Gabarrell
Department of Chemical Engineering, Universitat Autònoma de Barcelona (UAB), Bellaterra (Cerdanyola del Vallès), 08193 Barcelona, Spain

quality, avoiding unnecessary operations, improving the efficiency of management operations, and increasing tree density.

Keywords Cork · Environmental impact · Life cycle assessment (LCA) · *Quercus suber* L. · Southern Europe

1 Introduction

Cork is a natural material that consists of a thick and continuous layer of suberized cells that cover the stems and branches of the cork oak tree (*Quercus suber* L.). Cork oak forests and woodlands cover an area of almost 2.1 million hectares, mainly in countries of the Western Mediterranean Basin such as Portugal, Spain, Morocco, Algeria, Tunisia, France, and Italy (APCOR 2012). Portugal has the largest cork oak area followed by Spain, accounting for about 34 and 27 % of the global cork oak area, respectively (APCOR 2012). Portugal and Spain are also the leading producers of raw cork with shares of 50 and 31 % of the worldwide raw cork production, respectively (APCOR 2012).

Depending on its quality, raw cork has a wide range of applications such as natural cork stoppers, agglomerated cork stoppers, insulation panels, wall and floor coverings, gaskets, shoe insoles, household utensils, decorative products, and many other products used in building construction, industry, aerospace, fashion, and sports, among other sectors. The first cork harvest or stripping typically takes place when trees are 20–40 years old, but it can occur later depending on the particular environmental conditions (Pereira 2007). This cork (called virgin cork) has poor industrial quality and is used in the manufacture of agglomerates. Thereafter, cork is extracted every 9–14 years, depending on the region where cork oak stands are located (Pereira and Tomé 2004). The cork obtained in the second stripping (called second cork) has also low quality being only suitable for the production of agglomerates. The cork obtained from the third stripping onwards (called reproduction cork) has the best quality and is applied in the production of natural cork stoppers, the most profitable product, as well as in the production of other products from natural cork such as disks or decorative objects.

Cork oak forests and woodlands may contribute to climate change mitigation when they are sustainably managed as they sequester carbon dioxide (CO_2) from the atmosphere (Pereira et al. 2007, 2008). Besides, they are important reservoirs of fauna and flora biodiversity, provide opportunities for development in economically and socially disadvantaged areas, and play a key role in ecological processes, such as water retention and soil conservation (Bugalho et al. 2011; Silva et al. 2009; WWF 2006). However, several management activities are performed during the lifespan of cork oak, which can reach 200–250 years. These activities may consume fossil fuels, fertilizers, and other chemicals, resulting in impacts to the environment both on-site and along the supply chain of these materials. The environmental impacts associated with the production and extraction of raw cork have been evaluated from a life cycle perspective by González-García et al. (2013) for Portugal and Rives et al. (2012a) for Catalonia (Spain), using life cycle assessment (LCA). While the Catalonian study provides the impacts for both reproduction cork and cork by-products (virgin and second cork), the Portuguese study focuses the analysis only on reproduction cork. Moreover, the results of the two studies cannot be directly compared due to methodological differences in the functional unit, system boundaries, and allocation criteria.

What makes a comparison of cork production in these two regions particularly interesting is the fact that cork oak stands are managed according to two distinct silvicultural systems: cork oak woodlands in Portugal and cork oak forests in Catalonia. Cork oak woodlands (called *montados*) are multifunctional agro-forestry systems that usually combine cork production with pasture for livestock grazing or cereal crops. The tree density is low (usually 50–150 trees ha^{-1} during the productive period), the cork yield is about 200 kg ha^{-1} year^{-1}, and cork extraction is undertaken every 9 years (Pereira 2007; Rives et al. 2012a). In cork oak forests, tree density is higher (around 400 trees ha^{-1} during the productive period), not allowing the practice of agriculture underneath the trees. Due to worst climatic and environmental conditions, the cork yield in cork oak forests in Catalonia is lower than that in the Portuguese *montados*, about 150 kg ha^{-1} year^{-1}, and the cork is extracted every 12–14 years (Rives et al. 2012a). Both systems are not natural systems but they are the result of centuries of oriented silvicultural practices. In Portugal, most of the present mature cork oak stands were established by natural regeneration through fallen acorn germination, but artificial regeneration had a great increment in the 1990s due to incentives for afforestation of abandoned agricultural lands (Pereira 2007). The LCA study on Portuguese reproduction cork performed by González-García et al. (2013) was limited to the evaluation of cork oak stands established by plantation, while the life cycle impacts of stands established by natural regeneration in Portugal remain unstudied. In turn, most of the Catalonian cork oak stands are established by natural regeneration. For this reason, the LCA study on Catalonian raw cork carried out by Rives et al. (2012a) assessed stands established by natural regeneration.

The objectives of this study are threefold:

1. To evaluate the environmental impacts associated with the production of the three types of raw cork extracted from Portuguese *montados* from a cradle-to-gate perspective considering two alternative practices for stand establishment, i.e., plantation and natural regeneration.
2. To compare the environmental impacts of raw cork production in Portuguese *montados* and Catalonia cork oak

forests. LCA is applied based on the same methodological choices and assumptions (functional unit, system boundaries, allocation criteria, and impact assessment method) in order to allow a direct and reliable comparison of both cork production systems.

3. To assess the influence of using different allocation criteria for partitioning the environmental impacts between the different types of raw cork produced.

2 Methods

2.1 Functional unit

The functional unit is the production of 1 t of each type of raw cork (fully equilibrated) ready to be delivered to the cork processing industry.

The moisture content in cork is very variable. It is about 22–25 % for green cork just extracted from the tree. Around 21 days after the stripping, cork is considered to be fully equilibrated under ambient air conditions with moisture content of 6–10 %.

2.2 System boundaries

System boundaries are illustrated in Figs. 1 and 2 for cork produced in Portugal in stands established by plantation and natural regeneration, respectively. Figure 3 shows the system boundaries for cork production in Catalonia. The system boundaries include all the management operations carried out during the following stages: stand establishment, stand tending, cork stripping, and field recovery (only in Portugal). The production of fuels and chemicals consumed in all the stages was also considered, as well as the production of the machinery used to perform the operations. The transport of workers (within the cork oak woodland or forest) and materials was also included.

The following items were not considered due to lack of inventory data: (1) production of cork oak plants in nurseries (only applicable to Portugal) and (2) production of coloring and diffuse emissions derived from fungicide and coloring application (only used in Catalonia).

2.3 System description

2.3.1 Cork oak woodlands in Portugal

In Portugal, cork oak is the second most important tree species in terms of area occupation. Pure and dominant cork oak stands cover an area of about 737,000 ha, representing 23 % of the total forest area (ICNF 2013). About 90 % of the raw cork is produced in the Alentejo region (AFN 2010), and therefore, this study focuses on raw cork produced in this region located in the south of the country.

This study considers two alternative management models: stands established by plantation and stands originated by natural regeneration. The differences between these models are in the operations carried out during stand establishment and also in thinning operations (during stand tending stage), which are not performed in the natural regeneration model.

When stands are established by plantation, the stand establishment stage includes a first step of field preparation consisting in cut-over clearing (with disk harrow) and soil mobilization (furrow-hillock surface soil). Then, plants grown in a nursery are manually planted with a density of around 400 plants ha^{-1}. Together with plantation, PK fertilizer is manually applied to each plant. Approximately 1 year after the plantation, dead plants are substituted with new ones. In the natural regeneration model, no operations take place in the stand establishment stage.

The stand tending stage includes the following operations: cleaning of spontaneous vegetation (with rotary mowers to avoid root damage), pruning (the first is manual with pruning shears and the remaining are carried out with chainsaw), thinning (with chainsaw), and fertilizing (NPK fertilizer applied mechanically). Since the mortality of young trees may be very high, when stands are naturally regenerated, thinning takes place only occasionally to avoid competition between trees. Therefore, in this study, thinning is assumed to be dispensable.

The cork stripping stage begins when the trees are 20–30 years old, and cork stripping is repeated every 9 years with an axe. The cork harvested is cut into slabs of appropriate size and is transported up to the storage place (field yard). Finally, the field recovery stage consists in tree felling with a chainsaw when tree is approximately 170 years old. The stumps are not removed.

2.3.2 Cork oak forests in Catalonia

In Catalonia, cork oak covers 116,000 ha, being dominant in 63,000 ha, representing 12 % of the total area where cork oak is present in Spain (Burriel et al. 2004). As most of the Catalonian cork oak stands are originated by natural regeneration, this establishment practice was considered. Pure cork oak forests could comprise about 700 trees ha^{-1}, of which 400 are cork productive while 300 are in the initial phases of growth (CFC 2005). No operations are undertaken during the stand establishment stage.

The stand tending stage includes scratching (making vertical incisions manually), as well as cleaning of spontaneous vegetation and road maintenance, which were assessed jointly because data available refer to both operations. Moreover, these data also include occasional thinnings and felling of decrepit trees.

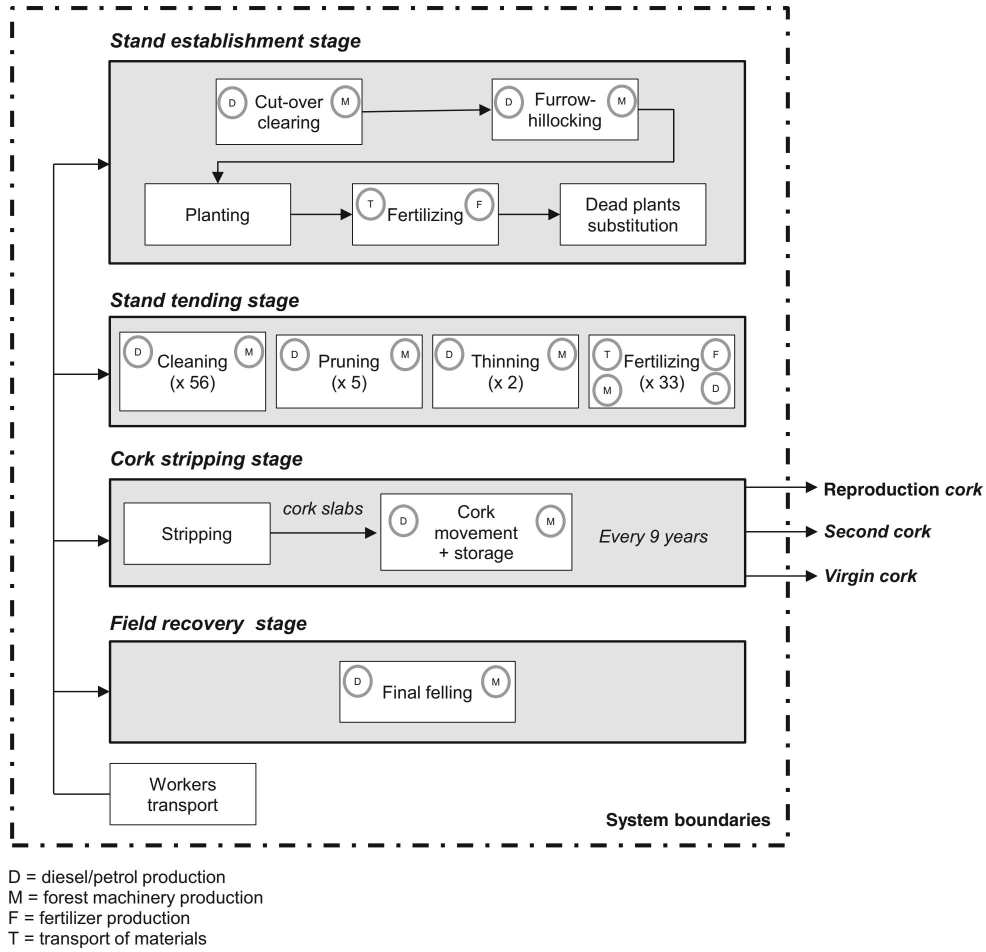


Fig. 1 System boundaries for cork production in Portugal in stands established by plantation

The cork stripping stage includes cork stripping every 13 years using axes, starting when trees are 35–40 years old. After cork stripping, a fungicide with a coloring is sprayed in the exposed tree trunk and cork slabs are transported to a storage place (field yard).

The lifespan of cork oak trees is considered to be 200 years, but the field recovery stage was not considered as trees are normally not felled. However, the felling of some decrepit trees is considered in the operation of cleaning and road maintenance in the stand tending stage, as referred above.

2.4 Allocation

Cork oak stands are multifunctional systems that produce different types of cork. Besides, wood from prunings, thinnings, and final felling is also produced, being mainly used for heating purposes, for example in house boilers, fireplaces, and industrial bakery ovens. Other products and services, such as honey, mushrooms, hunting, and tourism, are also commonly generated. In this study, by default, all the environmental impacts were allocated to cork because currently it is the primary product that articulates cork oak stands (Antunes et al. 2010; Boschmonart-Rives et al. 2013; Pinto-Correia et al. 2013). Two alternative criteria were applied to allocate the environmental impacts between the three different types of cork produced: mass and economic (based on market price). Table 1 shows the market prices and the allocation factors adopted.

In a sensitivity analysis, an alternative allocation approach was simulated by allocating environmental impacts also to the wood produced in the cork oak stands. In fact, all the inventory data, except those related with cork movement and storage, refer to the joint production of both cork and wood. No burdens were allocated to other products and services provided by the cork oak stands as the inventory data refer to activities that take place even if those products and services would not exist. In the sensitivity analysis, the same two criteria referred above (mass and economic) were applied to allocate the environmental impacts between cork (different types) and wood. The mass allocation procedure was applied to all operations as they benefit the tree as a whole. The exception is the operation of cork movement and storage, which was only allocated to the different

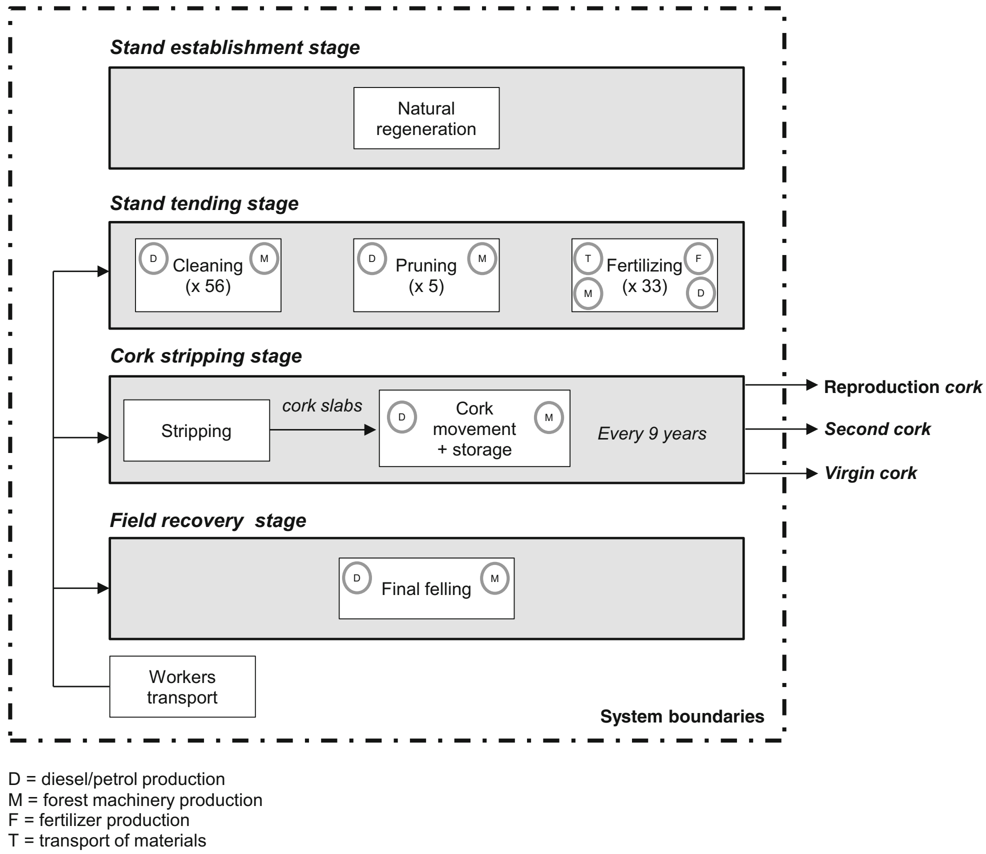


Fig. 2 System boundaries for cork production in Portugal in stands established by natural regeneration

types of cork. In the economic allocation, all operations were considered as cork prices refer to cork at the storage place. Table 2 presents the market prices and the allocation factors considered in this case.

2.5 Inventory analysis

Table 3 presents the inputs and emissions derived from fertilizer use associated with the production of 1 t of total raw cork (fully equilibrated) in the three systems assessed. Data on inputs for the Portuguese systems are primary data provided by associations of cork producers located in Alentejo. These data are average values estimated based on the typical ranges provided by those associations for each operation, as presented by González-García et al. (2013). The management models (i.e., type, sequence, and frequency of operations) are representative of the best management practices recommended nowadays. For the Catalonian system, data on inputs are also primary data. They were collected and averaged from five cork oak exploitations located in northeastern Catalonia, between the Pyrenees and the Costa Brava. These exploitations, which were considered to be representative of cork oak forests in Catalonia, are described in Rives et al. (2012a).

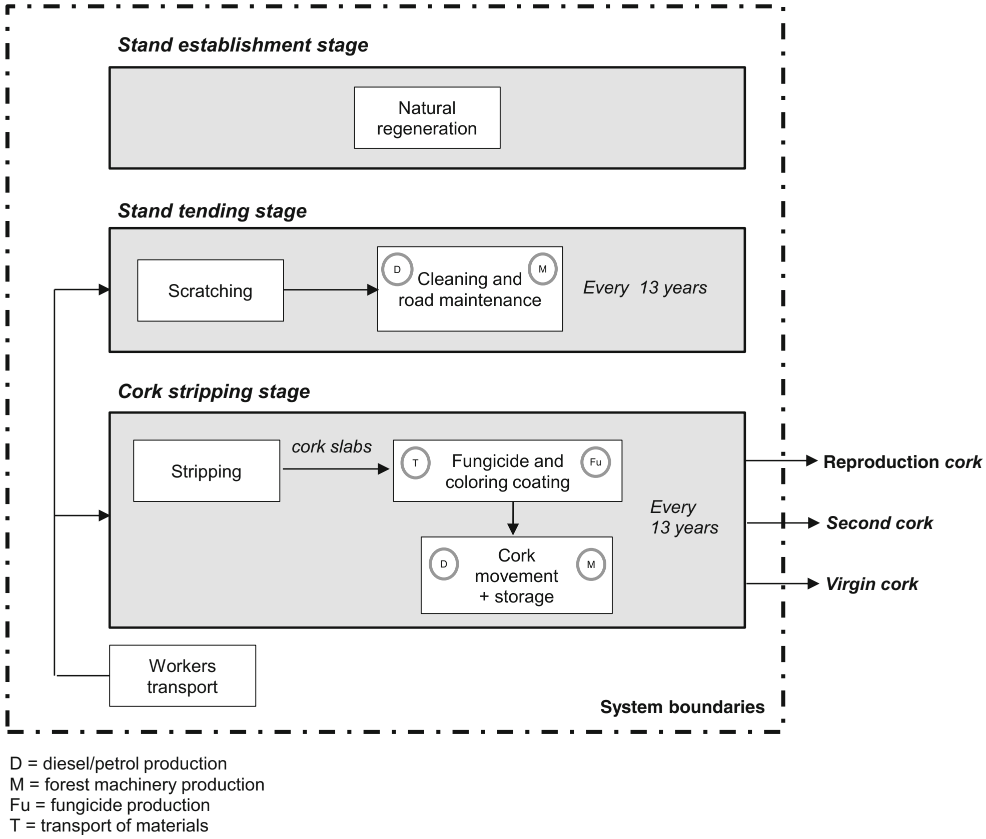
Emissions derived from the application of N-containing fertilizer include nitrous oxide (N_2O) and ammonia (NH_3) to air and nitrates (NO_3^-) to water. Emission factors of 0.01 kg N_2O–N, 0.1 kg NH_3–N, and 0.3 kg NO_3^-–N per kg of N in fertilizer were adopted (IPCC 2006). Application of P-containing fertilizer leads to phosphate (PO_4^{3-}) emissions to water. An emission factor of 0.01 kg PO_4^{3-} per kg of P in fertilizer was considered to calculate these emissions (Rossier 1998).

On-site emissions derived from fuel combustion in mechanized and motor-manual forest operations were estimated using emission factors taken from the Ecoinvent database (Ecoinvent 2010) (Table 4). This database was also the source of inventory data for the production of fuels (diesel and petrol), fertilizers, fungicide, and machinery (Table 4).

The distances and transport modes for the transport of the different materials and workers are presented in Table 5. They are primary data obtained as explained above for input data. Emission factors for each transport mode were taken from Ecoinvent (2010) (Table 5).

The amount of biogenic CO_2 assimilated in cork was assumed to be equal to the amount of CO_2 that will be released back to the atmosphere from cork oxidation (combustion and decay) along the downstream life cycle stages of cork (industrial processing and end-of-life). This is a common assumption in LCA studies of forest products (e.g., Dias and Arroja 2012; Silva et al. 2013).

Fig. 3 System boundaries for cork production in Catalonia



2.6 Impact assessment

The impact assessment was performed using the midpoint characterization factors recommended by the International Reference Life Cycle Data System (ILCD) (EC 2012) because these factors were considered to be the best available factors in a consultation process involving hearing of both scientific experts and stakeholders (Hauschild et al. 2013). During this process, the characterization models were assessed based on several criteria addressing both scientific quality and stakeholder acceptance or policy relevance. The following impact categories were considered: climate change (CC), ozone depletion (OD), human toxicity: cancer effects (HTC), human toxicity: non-cancer effects (HTNC), photochemical ozone formation (POF), acidification (A), terrestrial eutrophication (TE), freshwater eutrophication (FEu), marine eutrophication (ME), freshwater ecotoxicity (FEc), and mineral and fossil resource depletion (MFRD).

Other impact categories potentially relevant for the systems under study such as biotic resource depletion, land use, and water use were excluded due to immaturity and/or lack of scientific consensus in the impact assessment methodologies (Klinglmair et al. 2014; Kounina et al. 2013; Mattila et al. 2012).

Table 1 Default allocation factors

Product	Mass allocation		Economic allocation			
	Portugal	Catalonia	Portugal		Catalonia	
	Allocation factor (%)	Allocation factor (%)	Price (€/t)[a]	Allocation factor (%)	Price (€/t)[b]	Allocation factor (%)
Reproduction cork	96.8	86.5	1667	97.4	1900	96.8
Second cork	2.4	8.1	1667	2.4	400	1.9
Virgin cork	0.8	5.4	433	0.2	400	1.3

[a] Price of fully equilibrated cork; source: ANSUB—Associação de Produtores Florestais do Vale do Sado (personal communication)

[b] Price of fully equilibrated cork; source: Raddi (2013)

Table 2 Allocation factors in the sensitivity analysis

Product	Mass allocation		Economic allocation			
	Portugal	Catalonia	Portugal		Catalonia	
	Allocation factor (%)[a]	Allocation factor (%)[a]	Price (€/t)[d]	Allocation factor (%)	Price (€/t)[e]	Allocation factor (%)
Reproduction cork	30.0	24.7	1667	90.7	1900	85.3
Second cork	0.7	2.3	1667	2.2	400	1.7
Virgin cork	0.3	1.6	433	0.2	400	1.1
Wood	69.0[b]	71.4[c]	30	6.9	50	11.9

[a] Dry basis

[b] Wood production estimated with the SUBER v5.0 model (Paulo et al. 2012)

[c] Boschmonart-Rives et al. (2013)

[d] ANSUB—Associação de Produtores Florestais do Vale do Sado (personal communication)

[e] Raddi (2013)

3 Results

Table 6 presents the impact assessment results associated with the production of 1 t of each type of cork in Portugal (in stands established by plantation and natural regeneration) and in Catalonia, obtained with mass and economic allocation in the default allocation approach in which all impacts were allocated to cork. A detailed analysis of the results obtained for Portugal is given in “Section 3.1.” The comparison of the results obtained in the two regions under study is provided in “Section 3.2.” Finally, “Section 3.3” presents the results obtained for the sensitivity analysis on allocation.

3.1 Environmental impacts of Portuguese cork

The impacts associated with cork produced in cork oak stands established by plantation are higher than those associated with cork produced in cork oak stands established by natural regeneration, regardless of the type of cork and the allocation criteria (Table 6). This is because stand establishment operations and thinnings are absent in stands originated from natural regeneration. However, the difference between the two systems is smaller than 5 % for all the impact categories other than photochemical ozone formation. For this impact category, the difference is around 10 %. Figures 4 and 5 show, respectively, that the stand establishment stage and the thinning operation have small contributions (up to 4 and 2 %, respectively) to the total impacts of the system based on plantation for all impact categories other than photochemical ozone formation, which explains the small differences. For photochemical ozone formation, the contribution of the stand establishment stage is only 2 % but the thinning operation accounts for 8 % of the total impacts, resulting in a higher reduction in the natural regeneration system in relation to the plantation system. It should be noted that although Figs. 4 and 5 present results obtained by applying mass allocation, the relative contribution of each stage and operation is the same when economic allocation is applied.

Within each management scenario (plantation or natural regeneration), the impacts obtained per tonne of each type of cork are exactly the same when mass allocation is applied. On the contrary, when economic allocation is applied, virgin cork has a much lower impact since its market price is also much lower (Table 1), being its impact 26 % of the impact of reproduction cork. Reproduction and second cork have similar impacts as they have similar market prices (Table 1).

For both reproduction and second cork, the choice of the allocation procedure is irrelevant, with economic allocation generating impacts that are only 1 % higher than those obtained with mass allocation. The allocation criteria affect significantly the results obtained for virgin cork, which are 26 % lower with the economic allocation in comparison with the mass allocation.

The stage that contributes most to the total impact, regardless of the cork type and allocation criteria, is the stand tending stage, with shares ranging from 75 % (in photochemical ozone formation) to 98–99 % (in acidification and eutrophication-related impacts) (Fig. 4). Within the stand tending stage (Fig. 5), fertilizer production plays a key role for climate change, ozone depletion, human toxicity (cancer effects), freshwater eutrophication, freshwater ecotoxicity, and resource depletion, with contributions ranging from 35 to almost 90 % of the impacts. On-site emissions arising from fertilizer use are particularly important for acidification and terrestrial eutrophication (mainly due to NH_3) and marine eutrophication (mainly due to NO_3^-), contributing to 67, 84, and 90 % of the impact of the stand tending stage, respectively. Cleaning operations dominate the impact of human toxicity (non-cancer effects), contributing to almost 50 % of the impact of the stand

Table 3 Inventory data associated with the production of 1 t of total raw cork (fully equilibrated)

	Portugal—plantation	Portugal—natural regeneration	Catalonia
Inputs			
Plants (number)	14	–	–
PK fertilizer (kg)[a]	0.93	–	–
NPK fertilizer (kg)[b]	3.23	3.23	–
Fungicide (thiophanate-methyl 45 %) (kg)	–	–	0.16
Coloring (tekron) (L)	–	–	0.13
Water (L)	–	–	120
Diesel (kg)			
Cut-over clearing	0.37	–	–
Furrow-hillocking	0.56	–	–
Cleaning	6.24	6.24	–
Fertilizing	4.51	4.51	–
Cleaning and road maintenance			1.70
Petrol (kg)			
Pruning	2.71	2.71	–
Thinning[c]	0.76	–	–
Final felling	1.83	1.83	–
Outputs			
Products			
Reproduction cork (t)	0.968	0.968	0.865
Second cork (t)	0.024	0.024	0.081
Virgin cork (t)	0.008	0.008	0.054
Emissions from fertilizer use[d]			
N_2O to air (kg)	0.12	0.12	–
NH_3 to air (kg)	0.91	0.91	–
PO_4^{3-} to water (kg)	0.10	0.10	–
NO_3^- to water (kg)	9.93	9.93	–

[a] 22.5 % P_2O_5, 5 % K_2O

[b] 7 % N, 21 % P_2O_5, 21 % K_2O

[c] About 50 % of the trees are cut in each thinning operation

[d] Total on-site emissions associated with the production of raw cork include also emissions from fuel combustion, which were calculated using emission factors from Ecoinvent (2010) (Table 4)

tending stage, mainly due to emission of zinc to soil resulting from rotary mower operation. Finally, pruning operations have the largest contribution to photochemical ozone formation (about 40 %) as a result of non-methane volatile organic compounds (NMVOCs) from chainsaw use.

The remaining stages have much smaller contributions than the stand tending stage. Stand establishment stage accounts for 1 to 4 % of the total impact when stands are established by plantation and has no impacts when the stands are naturally regenerated. The impacts from the cork stripping stage tend to be higher than those from the stand establishment for all impact categories, representing up to 7 % of the total impacts. Most of the impacts arisen in this stage come from cork movement and storage (Fig. 6). The field recovery stage, consisting in final tree felling with chainsaw, has no significant impacts (smaller than 5 %) except for the impact category of photochemical ozone formation, where it accounts for around 20 % of the total impacts. The reason for this contribution is the emission of NMVOCs during chainsaw use.

3.2 Comparison with cork produced in Catalonia

When mass allocation is applied, raw cork produced in Catalonia presents a better environmental profile than raw cork produced in Portugal for all the impact categories analyzed (Table 6). For the impact category of human toxicity (non-cancer effects), the impact in Catalonia is about half of the impact in Portugal, but for the remaining impact categories, the impacts in Catalonia are much lower, ranging from 2 to 25 % of the impacts in Portugal.

The relative contributions of each stage to the total impacts of cork produced in Catalonia are shown in Fig. 4. The stages of stand establishment and field recovery have no impacts as stands are established by natural regeneration and tree felling is not a usual practice. However, felling of some decrepit trees is being considered in the operation of cleaning and road maintenance in the stand tending stage. The stand tending stage is the main hot spot in Catalonia, accounting for 52 to 76 % of the total impacts. However, the impacts from stand tending operations are much smaller than in Portugal. In

Table 4 Summary of data taken from Ecoinvent (2010)

Process/operation	Name of Ecoinvent process
PK fertilizer	Triple superphosphate, as P_2O_5, at regional storehouse/RER; potassium chloride, as K_2O, at regional storehouse/RER
NPK fertilizer	Ammonium sulfate, as N, at regional storehouse/RER; triple superphosphate, as P_2O_5, at regional storehouse/RER; potassium chloride, as K_2O, at regional storehouse/RER
Fungicide (thiophanate-methyl 45 %)	[Thio] carbamate-compounds, at regional storehouse/RER
Water	Tap water, at user/RER
Fuel and machinery consumption and emissions from	
Cut-over clearing	Tillage, harrowing, by rotary harrow/CH (adapted to diesel consumption of disk harrow in Portugal)
Furrow-hillocking	Tillage, harrowing, by rotary harrow/CH (adapted to diesel consumption of furrow-hillocking in Portugal)
Cleaning	Mowing, by rotary mower/CH
Fertilizing	Fertilizing, by broadcaster/CH
Cleaning and road maintenance	Transport, tractor and trailer/CH
Pruning	Power sawing, without catalytic converter/RER
Thinning	Power sawing, without catalytic converter/RER
Final felling	Power sawing, without catalytic converter/RER

Catalonia, stand tending includes only cleaning, road maintenance, and worker transport to perform these operations, whereas in Portugal, this stage encompasses much more operations, which explains the largest differences between the two regions (Fig. 5). It should be also noted that cleaning operations in Catalonia are undertaken less frequently than in Portugal, resulting in lesser impacts for all the categories analyzed. The cork stripping stage accounts for 24 to 48 % of the total impacts in Catalonia. In this region, the impacts from the cork stripping stage are dominated by cork transport from the tree up to the storage place (33–96 % of the impacts of this stage) (Fig. 6), although worker transport has also relevant impact in particular for climate change and ozone depletion. The impacts associated with these operations in Catalonia are higher than in Portugal because the distances traveled are also higher in Catalonia than in Portugal. In Catalonia, fungicide production plays a major role in freshwater eutrophication with 53 % of the total impact. Fungicide is not applied in Portugal.

When economic allocation is applied to estimate the impacts of reproduction cork, the trends obtained with mass allocation for Portugal and Catalonia are still valid. Regarding the impacts obtained for virgin and second cork in Catalonia, they are similar, being equal to 21 % of the impacts obtained for reproduction cork due to lower market prices (Table 1). Besides, for the same reason, they are also much smaller than the impacts obtained with mass allocation. A comparison of the impacts obtained for virgin and second cork in Portugal and Catalonia shows that the impacts in Catalonia are much lower because management practices are less intensive, as explained above. The difference in the impacts is more significant for second cork as the market prices greatly differ in the two regions (Table 1).

3.3 Sensitivity analysis on allocation

Figure 7 presents the results obtained with the four allocation criteria for the impact category of climate change, as an illustrative example. For the remaining impact categories, the trends are similar. The results obtained with mass allocation when both cork and wood are considered as co-products are much smaller than those obtained with mass allocation when only cork is considered as primary product (default approach), being only 31–36 % of the default result for Portugal and 38–45 % of the default result for Catalonia,

Table 5 Transport profile

System	Material/workers	Distance (km)[a]	Name of Ecoinvent process
Portugal (plantation and natural regeneration)	Fertilizers	50	Transport, lorry >6 t, fleet average/RER
	Cork to storage place	3	Transport, tractor and trailer/CH
	Workers	3	Transport, passenger car, diesel, fleet average 2010/RER
Catalonia	Fungicide	50	Transport, van <3.5 t/RER
	Coloring	50	Transport, van <3.5 t/RER
	Cork to storage place	6	Transport, tractor and trailer/CH
	Workers to stripping	6	Transport, passenger car, diesel, fleet average 2010/RER
	Workers to scratching	1.9	Transport, passenger car, diesel, fleet average 2010/RER
	Workers to cleaning and road maintenance	3.2	Transport, passenger car, diesel, fleet average 2010/RER

[a] This distance corresponds to an outward journey. A round trip with an empty and a full return journey was considered in the calculations for the transport of materials and workers, respectively

Table 6 Impact assessment results associated with the production of 1 t of each type of cork in Portugal in stands established by plantation (Pt-P) and natural regeneration (Pt-NR) and in Catalonia (Cat), obtained by using mass and economic allocation in the default allocation approach

Impact category	Unit	Mass allocation[a]			Economic allocation								
		Pt-P	Pt-NR	Cat	Pt-P			Pt-NR			Cat		
					Reproduction cork	Second cork	Virgin cork	Reproduction cork	Second cork	Virgin cork	Reproduction cork	Second cork	Virgin cork
CC	kg CO_2 eq	196	188	24.8	197	197	51.4	189	189	49.3	27.7	5.84	5.83
OD	kg CFC-11 eq	2.03 E-05	1.92 E-05	3.22 E-06	2.04 E-05	2.04 E-05	5.33 E-06	1.93 E-05	1.93 E-05	5.04 E-06	3.61 E-06	7.60 E-07	7.58 E-07
HTC	CTUh	9.51 E-06	9.03 E-06	2.23 E-06	9.57 E-06	9.57 E-06	2.50 E-06	9.09 E-06	9.09 E-06	2.37 E-06	2.49 E-06	5.25 E-07	5.24 E-07
HTNC	CTUh	9.97 E-05	9.65 E-05	4.88 E-05	1.00 E-04	1.00 E-04	2.61 E-05	9.71 E-05	9.71 E-05	2.53 E-05	5.47 E-05	1.15 E-05	1.15 E-05
POF	kg NMVOC eq	2.42	2.16	0.164	2.43	2.43	0.634	2.18	2.18	0.568	0.184	0.0388	0.0387
A	mole H^+ eq	4.44	4.38	0.156	4.47	4.47	1.17	4.40	4.40	1.15	0.174	0.0367	0.0366
TE	mole N eq	15.9	15.6	0.566	16.0	16.0	4.17	15.8	15.8	4.11	0.633	0.133	0.133
FEu	kg P eq	0.382	0.378	0.00654	0.385	0.385	0.100	0.380	0.380	0.0992	0.00732	0.00154	0.00154
ME	kg N eq	2.69	2.67	0.0524	2.71	2.71	0.707	2.69	2.69	0.701	0.0587	0.0124	0.0123
FEc	CTUe	209	202	52.3	211	211	55.0	203	203	52.9	58.6	12.3	12.3
MFRD	kg Sb eq	0.00383	0.00371	9.75 E-04	0.00385	0.00385	0.00100	0.00373	0.00373	9.74 E-04	0.00109	2.30 E-04	2.29 E-04

[a] The results obtained with the mass allocation per tonne of each type of cork are the same for reproduction cork, second cork, and virgin cork

depending on the impact category. This is explained by the high amount of wood that is produced (about 70 % in dry basis) when compared to cork.

When economic allocation is applied, the results obtained with the two allocation approaches are not so different as when mass allocation is used. The impacts obtained when both cork and wood are considered as co-products are 93 and 88 % of the impacts given by the default approach, respectively for Portugal and Catalonia. This is because wood has a much lower market price when compared to cork (Table 2) and, therefore, the allocation factors to wood are only 6.9 and 11.9 % for Portugal and Catalonia, respectively.

4 Discussion

This study evaluates the environmental profile of reproduction cork, second cork, and virgin cork in the most productive region of Portugal (Alentejo). These different cork types are raw materials of different cork products produced not only in Portugal but also in other countries since Portugal is an exporter of raw cork (APCOR 2011). The obtained results can be integrated in LCA studies of products that have these different types of cork as raw materials. Most of the published LCA studies on cork products have been excluding raw cork production from the system boundaries (PwC/Ecobilan 2008; Rives et al. 2011, 2012b, c) or have been only considering raw cork production in Catalonia (Rives et al. 2013).

Two alternative practices for cork oak stand establishment were analyzed and compared in Portugal: plantation and natural regeneration. The results show that natural regeneration leads to lower impacts than plantation because fewer operations are performed, but the differences between the two scenarios is less than 10 % as the unnecessary operations (clearing, soil mobilization, fertilization at planting, and thinning) are not very relevant to the total impacts. Natural regeneration is also expected to be the better scenario regarding biodiversity because soil mobilization needed during stand establishment by plantation reduces the diversity of flora and fauna (Acácio 2009). Also, mature stands from natural regeneration are uneven-aged stands that create more habitats for fauna species than stands with an even-aged structure typical of plantations (Zavala et al. 2004). Natural regeneration is also the preferred method for the continuity of the stands because planted cork oaks have low survival rates (Almeida et al. 2009). However, in the disperse *montado* stands, there are some obstacles to the success of natural regeneration, such as overgrazing (livestock can damage young trees), lack of acorn dispersal agents, and dry and hot conditions (Pausas et al. 2009; Pereira 2007). Therefore, artificial regeneration is needed to complement natural regeneration in the perpetuation of

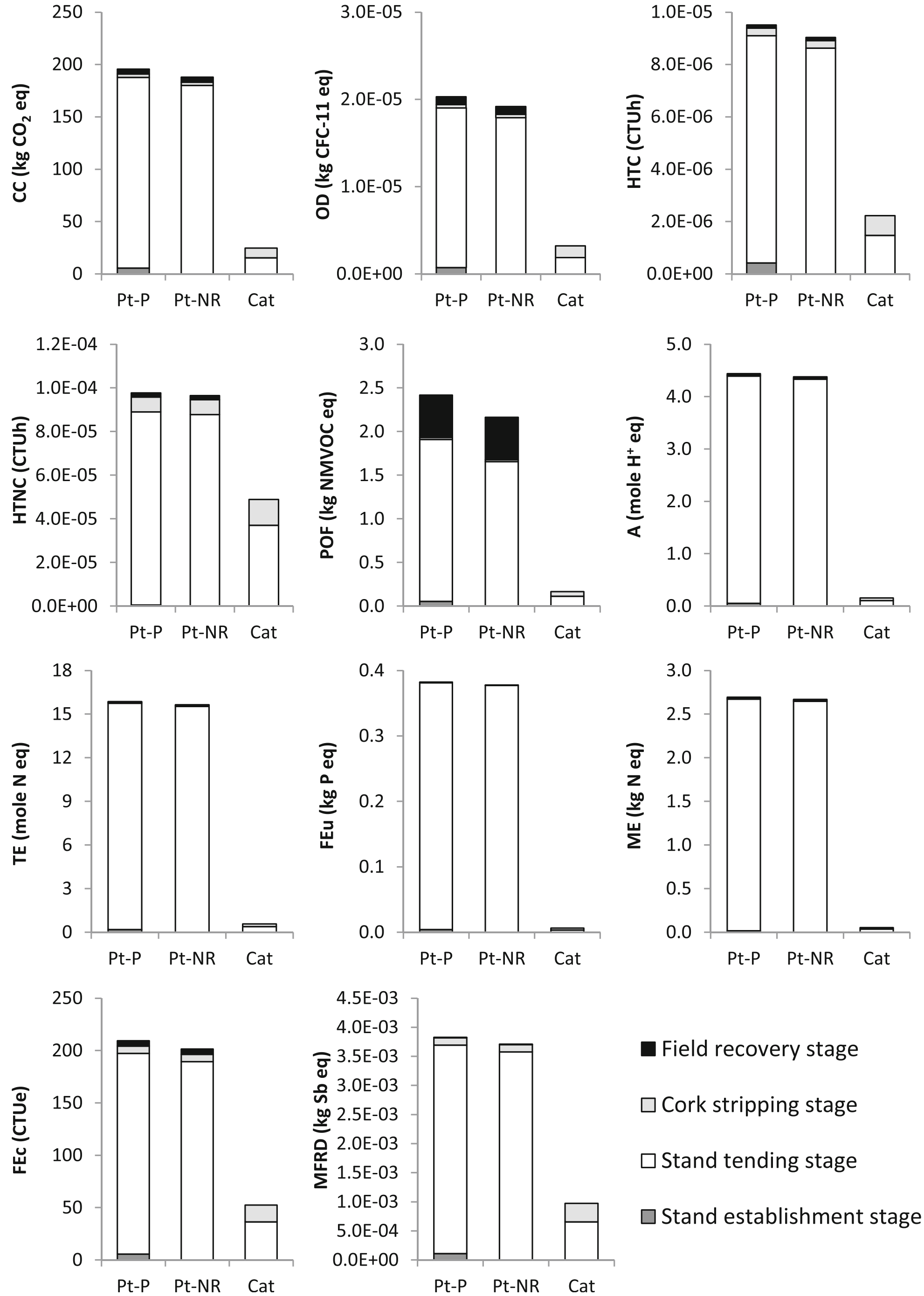


Fig. 4 Contribution of each stage to the impact assessment results obtained for 1 t of raw cork produced in Portugal in stands established by plantation (*Pt-P*) and natural regeneration (*Pt-NR*) and in Catalonia (*Cat*) using mass allocation in the default allocation approach

the cork oak stands. In cork oak forests, such as those in Catalonia, natural regeneration is more likely to succeed because the denser tree cover provides more shade, livestock is absent or rare, and more acorn dispersal agents are present (Acácio 2009; Pausas et al. 2009).

Although there is a global market, cork production depends on local features and, therefore, associated environmental impacts too. The environmental impacts obtained for cork produced in Portugal tend to be higher than for cork produced in Catalonia, mainly derived from differences in the intensity of the operations (cork oak woodlands require much more intensive practices than cork oak forests). However, there are also other factors that affect the results such as tree density, average cork yield, and distances traveled in the transport of cork and workers. These distances tend to be higher in Catalonia due to different reasons such as the hilly conditions with difficult accessibility and the size and organization of the forest property. In Portugal, cork oak woodlands in Alentejo commonly occupy plain areas with easy access. Nevertheless, it should be noted that some cork oak woodlands in Portugal

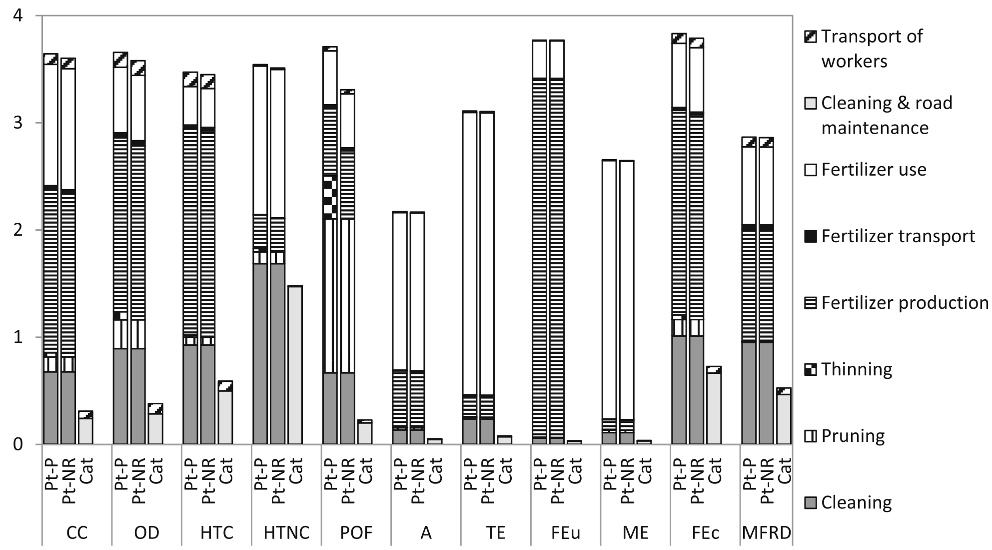


Fig. 5 Contribution of each process to the impact assessment results obtained in the stand tending stage, using mass allocation in the default allocation approach. The results refer to the production of 1 t of raw cork produced in Portugal in stands established by plantation (*Pt-P*) and natural regeneration (*Pt-NR*) and in Catalonia (*Cat*). Units: *CC* (kg CO_2 eq×50), *OD* (kg CFC-11 eq/2×10^{-5}), *HTC* (CTUh/4×10^{-5}), *HTNC* (CTUh/4×10^{-4}), *POF* (kg NMVOC eq/2), *A* (mole H^+ eq×2), *TE* (mole N eq×5), *FEu* (kg P eq/10), *ME* (kg N eq), *FEc* (CTUe×50), *MFRD* (kg Sb eq/800)

combine cork production with pasture for livestock grazing (mainly cattle but also sheep, goats, and swine) or cereal crops in the same land area. Moreover, several other products (such as mushrooms, honey, or aromatic plants) and socio-economical activities or services (such as rural tourism or hunting) are carried out in both Portuguese and Catalonian systems. Although the consideration of the total products, activities, and services provided can be very interesting in the comparison of these multifunctional systems, this can be complex and requires future research. Most of these products or activities can represent a benefit for society, and not only for exploitation owners.

The main hot spots are different in the two regions. In Catalonia, cleaning and road maintenance account for 45 to 75 % of the total impacts, while worker transport and cork transport have also important contributions (1–30 % and 14–23 % of the total impacts, respectively). In Portugal, the impacts mostly derive from fertilization. The impacts

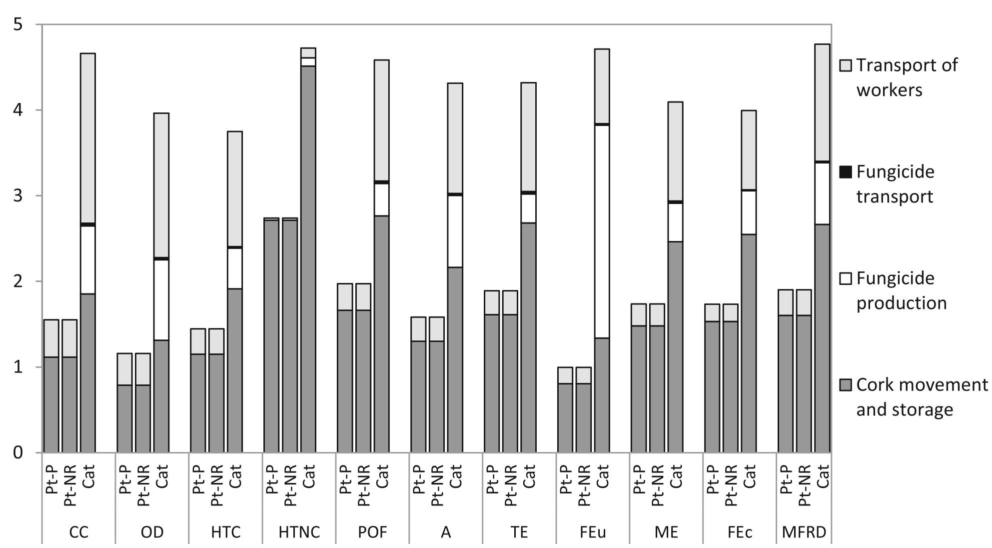
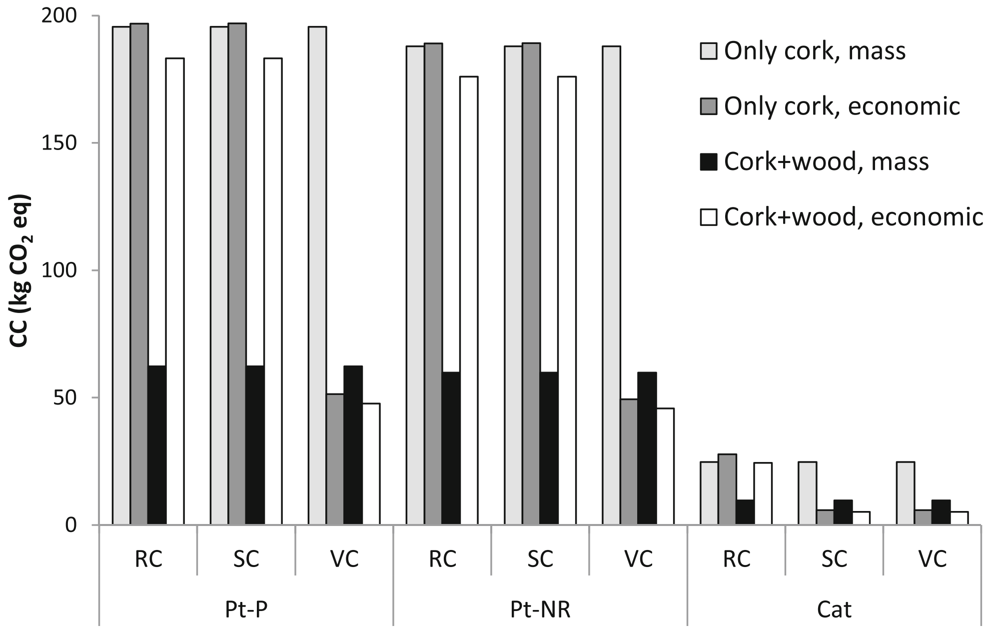


Fig. 6 Contribution of each process to the impact assessment results obtained in the cork stripping stage, using mass allocation in the default allocation approach. The results refer to the production of 1 t of raw cork produced in Portugal in stands established by plantation (*Pt-P*) and natural regeneration (*Pt-NR*) and in Catalonia (*Cat*). Units: *CC* (kg CO_2 eq×2), *OD* (kg CFC-11 eq/3×10^{-6}), *HTC* (CTUh÷5×10^{-6}), *HTNC* (CTUh/4×10^{-5}), *POF* (kg NMVOC eq/90), *A* (mole H^+ eq/8), *TE* (mole N eq/25), *FEu* (kg P eq/1500), *ME* (kg N eq/250), *FEc* (CTUe×4), *MFRD* (kg Sb eq/15,000)

Fig. 7 Results of the sensitivity analysis on allocation for the impact category of climate change. The results refer to the production of 1 t of each type of cork (reproduction cork (*RC*), second cork (*SC*), and virgin cork (*VC*)) in Portugal in stands established by plantation (*Pt-P*) and natural regeneration (*Pt-NR*) and in Catalonia (*Cat*)



associated with fertilizer production, transport, and application (field emissions) account for 44–98 % of the total impact for all categories, except for photochemical ozone formation. For this impact category, the main hot spot is pruning, which contributes to about 30 % of the total impact. In the impact category of human toxicity (non-cancer effects), cleaning operations are also relevant with a contribution similar to that from fertilization (about 43 %).

In order to decrease the environmental impact in the two regions, different strategies should be implemented. In Catalonia, one measure could be the introduction of livestock in cork oak forests in order to decrease the need of mechanized cleaning and road maintenance. Other measures should include a better planning and organization of cork and worker transport. In Portugal, special attention should be given to decrease the impacts derived from fertilization. The dosage of fertilizers should be adequate to the soil characteristics and excess fertilizers should be avoided. Besides, soil fertility could be improved by installing nitrogen-fixing crops and pastures that improve soil quality (Sousa et al. 2007). Other improvement measures consist in avoiding unnecessary operations and in improving the efficiency of the operations, in particular pruning and cleaning, in order to decrease fuel requirements and, consequently, combustion emissions. An increase in tree density (and consequently in cork productivity provided that tree competition is avoided) would also improve the environmental performance.

One of the objectives of this study was to evaluate how the choice of the allocation criterion would affect the outcomes. Allocation is a complex subject in LCA, and there is often the difficulty to clearly identify the most appropriate allocation criterion (EC 2010). The results of this study show that in the default allocation approach, the allocation criterion (mass or market price) has little effect (difference of 1 %) on the impacts of reproduction cork and second cork in Portugal because the allocation factors are similar for both allocation criteria. However, for virgin cork, the differences are remarkable, with the impacts being about 75 % lower when economic allocation is applied due to the lower market price of virgin cork. In Catalonia, the impacts of reproduction cork are 12 % higher when economic allocation is applied compared to mass allocation. The differences are more significant for second and virgin cork, which present impacts about 75 % lower when economic allocation is applied due to lower market prices of these cork types. Therefore, the choice of the allocation criteria is particularly relevant for virgin cork in Portugal and both virgin cork and second cork in Catalonia. When both cork and wood are considered as co-products in the allocation, the results obtained with economic allocation are not very different from those obtained with the economic allocation in the default approach. In contrast, when mass allocation is applied, the impacts are significantly lower than those estimated in the default approach with mass allocation. This means that the majority (64–69 % in Portugal and 55–62 % in Catalonia) of the impacts of the cork oak stands would be allocated to wood. The adoption of this criterion seems to be inappropriate as it would not create incentives for a sustainable management of cork oak ecosystems. In fact, these systems are exploited with the main objective of producing cork, but with this criterion, the impacts from cork production would be much lower and, therefore, impacts resulting from bad management practices would be mostly allocated to wood rather than to cork. Thus, although in the allocation hierarchy recommended by the ISO 14044 standard (ISO 2006) a mass

allocation should be preferred instead of an economic allocation, the latter criterion seems to be more meaningful in this case. It should be noted that when the objective is to identify the main hot spots in raw cork production, the allocation criteria are irrelevant since the relative contributions of each stage or operation remain the same, regardless of the allocation procedure applied.

In this study, biogenic CO_2 is assumed to be neutral, i.e., the amount of CO_2 removed from the atmosphere due to cork growth is equal to the amount of CO_2 emitted from cork oxidation along the life cycle. However, additional research is necessary in order to estimate a more accurate CO_2 balance taking into account carbon storage in cork products (both in use and in solid waste disposal sites) and the time delay between CO_2 sequestration by cork and CO_2 emission from cork oxidation. Furthermore, if the total CO_2 removed from the atmosphere by cork oak trees is allocated to cork, as assumed in this study for the environmental burdens considered, the biogenic CO_2 balance is expected to be a net CO_2 sequestration for the time horizon of 100 years, which is considered here for the impact category of climate change (Gràcia et al. 2010; Pereira et al. 2007, 2008). In fact, cork oak trees live for more than 100 years and keep sequestering CO_2 during their life span of 170–200 years. Besides, cork harvest has negligible impacts on the CO_2 balance, as cork represents only about 4 % of the total biomass produced between successive cork extractions (Bugalho et al. 2011).

The results obtained in this study are affected by both uncertainty and variability in parameters. Uncertainty results from a lack of knowledge about the real values of a quantity, and variability derives from the natural heterogeneity of the values (Basset-Mens et al. 2006). While uncertainty may be reduced by additional research, variability may not be reduced because it reflects real-world differences (Steinmann et al. 2014). According to Rives et al. (2012a), variability for Catalonian data is relatively slow for the consumption of fungicide, coloring, and water (−5 to +12 %) but is significant for data related with transport and machinery distances (up to −71 to +126 %). For Portugal, given the large area of cork oak woodlands and the nature of the operations carried out, variability is expected to be high for some data. For instance, the amount of fertilizer applied may vary considerably from exploitation to exploitation depending on soil quality and availability of technical advice, among other factors. Fuel consumption (and associated air emissions) from mechanized operations may also vary widely from exploitation to exploitation, depending on several factors such as experience of the machinery operator, size of spontaneous vegetation, or dimension of the cork oak stand. In addition to parameter uncertainty and variability, results are also affected by model uncertainty because the calculation model may not fully capture real processes. For example, the cork oak management models adopted in this study consider a certain type and number of operations that are recommended nowadays as best practices. Actually, these models may not be applied over the entire cork oak forests and woodlands, as practices may vary from exploitation to exploitation. Besides, current practices are assumed over the entire life cycle of the cork oak trees. The results are also affected by uncertainty due to normative choices as demonstrated by the sensitivity analysis on allocation.

A direct comparison of the results obtained in this study with those obtained in other research studies on raw cork production (i.e., González-García et al. (2013) for Portugal and Rives et al. (2012a) for Catalonia) is misleading due to different methodological assumptions concerning boundaries and impact assessment methodology.

5 Conclusions

Cork oak stands are managed differently in Portugal (Alentejo region) and Catalonia. In Portugal, cork oak stands are agro-silvopastoral systems with low tree density that are managed in a more intensive way. In Catalonia, they are forest systems with a higher tree density, fewer mechanized operations, and no fertilization. As a result of these differences, cork produced in Portugal tends to have higher impacts than cork produced in Catalonia.

The environmental hot spots in the two regions are also distinct. In Catalonia, they consist of cleaning, road maintenance, and worker and cork transport, whereas in Portugal, they include fertilization, pruning, and cleaning. Improvement options in Catalonia should be oriented to facilitate the introduction of livestock in cork oak forests in order to reduce mechanized cleaning and road maintenance. Furthermore, a better planning would contribute for minimizing transport of cork and workers. Improvement measures in Portugal include optimization of fertilizer dosage, plantation of nitrogen-fixing crops and pastures that improve soil quality, avoidance of unnecessary operations, efficiency improvement of the motor-manual and mechanized operations, and increase of tree density.

In Portugal, stands established by natural regeneration have a better environmental profile than stands established by plantation, but the differences are less than 10 %. The two perpetuation practices are complementary since natural regeneration is insufficient in the cork oak woodlands.

The allocation criteria (mass and market price) applied in the default approach (allocation only to cork) generate significantly different results for virgin cork in Portugal and both virgin cork and second cork in Catalonia. When wood is considered as a co-product, the adoption of mass allocation seems inappropriate and, thus, should be avoided as it would not create incentives for a sustainable management of cork oak ecosystems.

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